

LIDAR PAST, PRESENT, AND FUTURE IN NASA'S EARTH AND SPACE SCIENCE PROGRAMS

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ABSTRACT

Lidar is firmly entrenched in the family of remote sensing technologies that NASA is developing and using. Still a relatively new technology, lidar should continue to experience significant advances and progress. Lidar is used in each one of the major research themes, including planetary exploration, in the Earth Sciences Directorate at Goddard Space Flight Center. NASA has and will continue to generate new lidar applications from ground, air and space for both Earth science and planetary exploration.

INTRODUCTION

NASA has been a major investor in lidar technology and applications from the 1960's starting with the development of ground-based satellite laser ranging systems for studying crustal dynamics and plate tectonics. The last three Apollo moon missions in the early 70's each carried a lidar altimeter to map the terrain elevations around prospective landing sites. In the 1980's NASA fielded several airborne atmospheric and oceanic lidars including some on high altitude jets and balloons. During the 90's we experimented with lidar altimeters on the Space Shuttle and in orbit around the Moon and Mars. More recently the first dedicated Earth orbiting lidar mission, ICESat, continues the NASA tradition of taking a leading role in lidar science and technology. Additional lidar satellite missions are in preparation and planning.

Lidar activities at NASA are primarily driven by geophysical science questions. The science observational needs and associated observational strategies set the goals for lidar measurements, instrument definition or technology development. On the other hand, a new approach or a new technology will often lead to new sensors for existing observational needs. An example is the development of small diode pumped lasers and lightweight telescopes, which together enabled the development of a small lidar

(the Mars Observer Laser Altimeter) for mapping the topography of Mars. In the Earth Sciences Directorate at Goddard Space Flight Center for example, lidar is used for a wide variety of geophysical measurements, supplying valuable observations to major Earth and Planetary science theme areas. Our lidar applications include precise laser ranging to cube-corner equipped satellites (see figure 1), measurements of surface topography and vegetation (altimetry), vertical profiling of aerosol and cloud optical properties, Doppler measurements of wind profiles, and measurements of atmospheric ozone, CO₂ and other trace species.

Goddard lidar teams are engaged in scientific studies using lidar instruments, development of new lidar techniques, technologies, instruments and applications. At last count we were using 7 ground-based, 9 airborne and 1 space-based platform, and have several new systems in various stages of development. And this is just Goddard. Other NASA centers, particularly LaRC, are also involved in lidar activities.

Having such a broad-based multi-disciplinary approach to sensor development can lead to new observational strategies that may involve a new combination of sensors, an application of a new technology, or a modified sensor addressing several science areas in a new way. The Geoscience Laser Altimeter System (GLAS) on the Ice, Cloud, and land Elevation Satellite (ICESat) mission is one example, where a single lidar based on new technology provides precision ice sheet and topographic profiling as well as atmospheric profile measurements. The new emphasis on space exploration for NASA is seen as an opportunity to expand the number and variety of applications for all observational technologies, including lidar. Our strengths in Earth Science Remote Sensing should serve us well in exploring the rest of the planets in our solar system.

SCIENCE THEMES AND STRATEGIC PLANS

Goddard's Earth Science research is divided into 6 areas, each of which are intimately coupled in some way to all of the others.

Earth's Carbon Cycle

We contribute to NASA's effort to reduce future uncertainties in climate predictions by improving models and developing new observations of the land, ocean, and atmospheric cycling of carbon. A polar Orbiting Carbon Observatory using a Differential Absorption Lidar (DIAL) along with other instruments is being considered for characterizing atmospheric CO₂ concentrations with spatially and temporally dense observations needed for locating and quantifying land and ocean surface sources and sinks of carbon. DIAL can provide measurements on the sunlit side of the planet whereas passive spectrophotometers cannot, thus fulfilling half of the required measurements needed to characterize diurnal and seasonal variations of atmospheric carbon.

A lidar using multiple wavelengths in the red and near-IR are contemplated for a new approach to mapping and monitoring changes in surface vegetation canopy height and biomass needed to understand carbon exchange between land and the atmosphere.

Atmospheric Composition (Chemistry)

NASA has long been a big supporter of the Network for the Detection of Stratospheric Change (NDSC), a set of high-quality remote-sounding research stations for observing and understanding the physical and chemical state of the stratosphere. Ozone and key ozone-related chemical compounds and parameters are measured and lidars constitute a major part of the instrument complement at most NDSC sites, measuring stratospheric ozone, temperature, water vapor and aerosols in the lower stratosphere.

Goddard currently fields three mobile lidar systems to profile aerosols, ozone and temperature, serving as the transfer standard for fixed-base lidars in the NDSC. These measurements are also designed to support the correlative measurement efforts required to validate satellite instruments. Operation from an aircraft enables the satellite's field of view to be sampled at high resolution thereby permitting a determination of how horizontal inhomogeneities in the constituent field impacts the retrieval

algorithm. Tropospheric Ozone and pollution transport has been a target of ground-based and airborne DIAL systems at LaRC for a number of years.

The Water and Energy Cycle

Goddard is one of the few institutions that has the capability to support the full range of activities needed to understand the Earth's water and energy cycle, ranging from small scale modeling and field investigations to global scale monitoring and modeling. Lidar is increasingly becoming a valuable tool for observing clouds, water vapor, and surface ice.

Unique retrievals of cloud parameters are being obtained from ICESat. Airborne and ground-based lidar and radar systems also provide information on cloud (and aerosol) profiles and physical properties. Systems include the Cloud Physics Lidar (CPL) and Cloud Radar System (95 GHz) that are integrated on NASA's ER-2 platform, and the ground-based and the Micro-Pulse Lidar Network (MPL-Net) and Scanning Raman Lidar (SRL) where the latter provides very detailed depictions of water vapor structures and processes.

Researchers at Goddard are also monitoring the size and thickness of the polar ice sheets through repeated elevation mapping with airborne, and most recently with the GLAS laser altimeter on-board ICESat.

NASA is actively pursuing technologies to take water vapor lidar to space in order to improve our observations of water vapor with greatly increased vertical resolution, as well as technologies to characterize and monitor clouds in three dimensions from space.

Climate Variability and Change

How ice sheets will respond to global warming is one of the most uncertain and important issues in global climate change. There is a concern, that the current rate of global warming may cause one or both of the continental ice sheets to begin to undergo large-scale disintegration. Analysis of this problem requires improved dynamical ice sheet models coupled to models or data for changing climate boundary conditions. What is needed most of all is precise information on how the ice sheets are responding to the moderate global climate change that is currently underway. Centimeter-scale ice sheet topography is the primary product provided GLAS. Together with planned field experiments, ICESat provides the

possibility of addressing the crucial issue of ice sheet stability and the impact of climate change on the ice sheets. Sea ice thickness is also being determined from GLAS data. Realistic analysis and modeling must treat the non-linear interactions among processes including surface melt, rainfall on the ice sheet, lubrication of ice sheet base, and the effect of rising sea level on buttressing ice shelves.

The CALIPSO satellite mission includes a lidar, which will provide vertical profiles of aerosol backscatter with more detailed and accurate profile information than can be obtained with passive measurements. CALIPSO will also measure the vertical distribution and optical depth of optically thin clouds, including sub-visual cirrus clouds. A polarization channel will provide an indication of cloud ice amount and a 3-wavelength infrared imager bore sighted with the lidar.

In addition to the aerosol data from GLAS, Goddard also has a ground-based effort of carrying out global observations of the height distribution of aerosols to address their direct and indirect effects on atmospheric temperature. The Micro-Pulse Lidar Network is a small but global network of automated lidars continuously measuring profiles of aerosol scattering and extinction at about a dozen sites distributed around the globe. MPL data is being used by about 50 scientists around the world studying man's influence on the atmospheric aerosol loading and its effects on the radiative forcing of the Earth's climate. MPL data are being used for algorithm development and validation efforts for satellite-based lidar sensors on NASA spacecraft such as GLAS and CALIPSO. Finally, MPL-Net data are being used in conjunction with transport models to better understand how aerosols are transported from their source regions to remote locations. When coupled with wind direction and speed information, the vertical distribution of aerosol trace materials also provides information on aerosol mass transport. Long-range transport of trace gases and aerosols is a dominating factor in the global chemical balance. We envision that in the near future, multi-sensor satellite data sets will be combined with ground-based networks to develop a measurement based aerosol climatology.

The Solid Earth

Monitoring the motion of earth's crust and its deformations is NASA's oldest and longest running lidar program, and commensurate with

the time scales of plate tectonics, we expect it to be around for many years in the future. By the accurate tracking and ranging to corner-cube studded satellites with ground-based lidars with ever-increasing accuracy and precision, the monitoring of cm/yr motions in the crustal plates has been realized. And we never cease improving the satellite laser ranging capabilities, continually incorporating the latest in laser and detector technologies.

Altimetry science involves development of new measurement technique approaches as well as related analysis techniques, such as the separation of biomass signals from those of the bald earth. Research resulting from altimeter data includes detection of faults and other neotectonic features through canopy cover. Altimetry data collected from a variety of platforms and systems is also used for studies of ocean tides, ocean dynamics, and sea-level variations.

Goddard is developing a new generation of autonomous satellite laser ranging systems (SLR 2000), and 3-D imaging lidar techniques that have important application to hazard studies as well as planetary surface mapping.

Planetary Exploration

The primary lidar-related planetary activity over the last decade has been the development and operation of the Mars Orbiter Laser Altimeter (MOLA) on the Mars Global Surveyor (MGS) mission. MGS was launched in 1996 and initial operations began at Mars in September 1997. Systematic mapping of Mars began February 1999 and MOLA provided active topographic measurements of Mars almost continuously through June 2001, and after that in a radiometer mode. The MOLA investigation produced the first accurate high-resolution shape and topographic map of Mars that has helped advance our understanding of the physical processes that have shaped the planet. MOLA's approximately 600 million measurements of surface elevation have revealed the most prominent feature of the shape of Mars is a slope like feature that extends from the south pole downhill to the north. This slope has significant implications for past hydrologic processes that occurred on Mars. Analysis of the MOLA measured topography over the polar caps over a full Mars year shows a variation consistent with the seasonal deposition and sublimation of CO₂. This change is an average of 1 to 1.5 meters at higher latitudes decreasing to less than 10 centimeters at latitudes 60N&S. From the

elevation change and mass an approximate density of the material (CO₂) has been derived to show that it is about half the density of CO₂ ice and therefore more likely to be a heavy snow or a form of surface frost. A significant discovery from the MOLA altimetry measurements is the cratering record of the northern hemisphere. The data show that the northern hemisphere is almost the same as the cratered highlands of the south, implying that the two surfaces are therefore of similar age. Previously, it was believed the southern highlands were much older. The temporal spreading of the MOLA laser pulse echoes provided a measure of surface variability within the 160-meter laser footprint. These observations have provided a global description of the roughness of the surface of Mars with 160 m spatial resolution. These measurements, in conjunction with topographic data, were used extensively in the selection of the landing sites for Mars 98, Mars Exploration Rovers 1 & 2 and Beagle 2. MOLA measurements of laser reflections from clouds have shown that there is a seasonal and geographic pattern to the clouds on Mars and that some are restricted to the regions over or near the polar caps at altitudes varying from elevations near zero to 20 km. Patterns within the cloud formations suggest a topographic origin for the structures and have raised the suggestion that these atmospheric reflections are strong evidence for a seasonal depositional process for CO₂, akin to snow, on Mars. During the more than 4 Earth years that MGS has been orbiting Mars, changes have been detected in the gravity field caused by the seasonal deposition and sublimation of CO₂ on the polar caps. This has enabled the masses of the seasonal caps to be estimated and compared with the Ames Global Climate Model for Mars. Since June 2001 MOLA continues to operate as a sensitive passive radiometer that measures the brightness of the solar illuminated Mars surface at 1064 nm. Data from this mode provides unique observations of the changing brightness of the polar caps due to the seasonal deposition and sublimation of carbon dioxide.

A new compact laser altimeter (MLA) has been developed at Goddard for the MESSENGER Discovery mission. The MLA instrument was delivered to the spacecraft in June 2003 for launch to Mercury in the Spring of 2004. The MLA design is an advanced version of MOLA, having one-third the mass at 7.2 kg, a quarter the volume, and at 5 to 10 cm, nearly an order of magnitude more precision than MOLA. The

MESSENGER mission will arrive at Mercury in 2009 and the Laboratory will lead the investigation to measure the librations of the planet, which will provide information on the state of Mercury's core.

Several new lidar measurement approaches and concepts for planetary exploration are being pursued, include developing the next generation of planetary lidar for surface and atmospheric measurements. An emphasis is on surface height imaging lidar, which offers the possibility of high spatial resolution coupled with ~10 cm vertical precision. These will use scanning or multiple-beam or multiple-spot laser transmitters coupled with multiple or array detectors and processing electronics. For planetary atmospheric measurements, our labs are addressing aerosol, CO₂ and water vapor lidar technologies. In all these cases the planetary work utilizes synergy from similar (but larger) efforts for Earth science measurements. New active optical (laser) transponder approaches are also being pursued for precise range measurements over inter-planetary distances. It is expected that this approach will be used to demonstrate optical tracking and communication links with planetary spacecraft and could also be used in ultra-precise gravity measurements.

ACKNOWLEDGEMENTS

We would like to acknowledge the various programs within the NASA Earth Science and Space Science Enterprises for their support of the various lidar activities across the agency, and for the cooperative arrangements with NOAA, DOE, DoD, IPO, NSF, the many Universities and other institutions that have contributed to NASA efforts in lidar technologies and applications.